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The Biodiversity Forecasting Toolkit: Answering the 'how much', 'what', and 'where' of planning for biodiversity persistence

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ABSTRACT

This research reports on a new approach to conservation assessment that seeks to extend the target-based model traditionally underpinning systematic conservation planning. The Biodiversity Forecasting Tool (BFT) helps answer three important questions relating to regional biodiversity persistence: 'how much' biodiversity can persist for a given land-management scenario; 'what' habitats to focus conservation effort on; and 'where' in the landscape to undertake conservation action. The tool integrates fine-scaled variability in vegetation composition and structure with spatial context, which is critical for ensuring the viability of populations. Thus, a raster data framework is employed which deems each location or gridcell in a landscape as contributing to biodiversity benefits to various degrees. At its simplest, just two spatial inputs, vegetation community types and vegetation condition, are needed. Drawing on, as a case-study, a broad-scale biodiversity assessment for NSW, Australia, this paper reports on the successful application of the BFT tool for a variety of functions ranging from interactive scenario evaluation through to conservation benefits mapping.

1. Introduction

1.1. Systematic conservation assessment

Systematic conservation planning aims to maximize the long-term persistence of biological diversity at a collective regional level. It was initially developed to address a shortcoming of approaches that assessed the conservation value of sites in isolation from one another. In particular it introduced the concept of complementarity – i.e. the potential for new conservation areas to complement a portfolio of existing, and/or selected, conservation areas by adding elements of biodiversity (e.g. species) not already represented within this portfolio (Faith et al., 2003; Ferrier, 2002; Margules and Sarkar, 2007; Margules and Pressey, 2000). Systematic conservation assessment (SCA) (*sensu* Ferrier and Drielsma, 2010; Knight et al., 2006; Moilanen, 2012) includes a broad set of methodologies and tools that seek to support the goals of systematic conservation planning (Ferrier et al., 2009; Ferrier, 2005; Margules and Sarkar, 2007; Margules and Pressey, 2000) through actions such as reserve establishment, habitat management, improvement and restoration (Moilanen, 2012).

Systematic conservation planning principles have been encapsulated within a number of GIS-based SCA tools (Sarkar et al., 2006). Among the most widely applied are C-Plan (Pressey et al., 2009), Marxan (Ball et al., 2009) and Zonation (Moilanen et al., 2009). SCA tools are typically designed to perform one or more of the following forms of assessment: optimal plan generation; conservation benefit mapping; interactive scenario evaluation; site-based assessment; and conservation status monitoring (Ferrier and Drielsma, 2010). The success of conservation plans rely on many factors besides the choice of assessment tools (Knight et al., 2006) and it is likely that the strengths of each tool makes it particularly suited to specific applications (Delavenne et al., 2012). Approaches to SCA differ in a number of ways. One major difference is in the biodiversity entities or level of biological organization that is examined. Entities can be a species, habitat types (communities, ecosystems), or genes. Tools such as C-Plan or Marxan are capable of considering multiple entities. They can also combine biological entities with other features including ecosystem services (Moilanen, 2012).

The regional scale is a useful frame for assessing the state and prospects of biodiversity as a whole (Soule and Tergorgh, 1999;

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Margules and Sarkar, 2007; Noss, 1983; Redford and Richter, 1999). A general modeling framework for undertaking regional-scale conservation assessment has been described by Ferrier and Drielsma (2010). It includes inbuilt flexibility allowing its main components to be 'extended' by adding rigor and refinement, where and when this is needed and where the added effort and methodological complexity can be justified.

The 'regional scenario' concept is central to this paper. We use the term generically to refer to any unique regime of land-uses, management actions and environmental conditions across a region at a defined point in time i.e. a regional scenario can describe "what has happened, what will happen, what can happen, and/or how a target can be achieved" (Börjeson et al., 2006). Within this schema of observations and possibilities, the dynamics of landscape can be described by a time-series of linked scenarios.

Conservation planning typically includes phases of project definition, development of strategies and measures (e.g. investment plans, strategic plans, management plans), implementation, adaptation and improvement (Nature Conservancy, 2007). It also has a parallel role in promoting collaborative learning and building discursive communities, catalyzing innovative community action, and helping to dissolve and avoid unproductive conflict (Meppem and Gill, 1998; Sterman, 1994; Trimbur, 1989).

We describe here the Biodiversity Forecasting Toolkit (BFT), a regional-scale, community-level (*sensu* Ferrier and Guisan, 2006) conservation assessment methodology and toolkit that we developed in response to emerging demands for analytical capabilities as we perceived them through our involvement with real-world conservation planning in New South Wales (NSW, Australia) over two decades. The BFT has been applied and iteratively improved since 2002. In contrast to reports that published conservation assessment methodologies have rarely resulted in conservation action (Sewall et al., 2011), applications of the BFT are increasing and its products are now well integrated into biological conservation praxis in NSW. However, until now the salient elements of its architecture have not been published except within individual project reports (see Appendix A).

The BFT extends the prevailing 'target-based approach' to SCA by incorporating elements of process-based modeling, drawn from Metapopulation Ecology, and it considers the complexity of contemporary landscapes by drawing on the principles of Landscape Ecology (Drielsma et al., 2007).

The toolkit includes conservation benefit mapping as well as interactive reporting capabilities, making it user-ready within a scenario planning, learning environment.

In order to illustrate the toolkit, we present an example from a recent case-study in which the BFT was used to undertake SCA for NSW, Australia.

1.2. Why the BFT?

Site-scale approaches to conservation assessment are well-established within conservation planning praxis (Oliver and Parkes, 2003; Parkes et al., 2003). They are designed to assess the potential impact (positive or negative) of individual management proposals, using property-level (site-based) data, interpreted within a regional context (Seddon et al., 2010). However, site-assessment methodologies are not well equipped to consider the combined (cumulative) effect on biodiversity of multiple management actions across an entire region. They cannot model dynamic interactions and complementarities between actions, assess and monitor the status of biodiversity in a whole region, or map potential benefits of management actions across regions. Yet, as conservation resources are limited, these capabilities are necessary to instill confidence that conservation investment is effectively targeted.

Box 1: Dimensions of Complexity in Biodiversity Assessment

1. **All biodiversity** – Despite its near overwhelming complexity, biodiversity conservation seeks to understand and to plan for the persistence of biodiversity in its entirely (Noss, 1990; Redford and Richter, 1999). It is not sufficient to focus on a subset of iconic species, species with economic importance, or those that are endangered. Taking such a piecemeal approach risks condemning common, low profile species and whole ecosystems to a pathway toward extinction.

   Not all species and ecosystems are necessarily equal from a conservation perspective. Those that are distinct (genetically or compositionally) are of particular interest (Vane-Wright et al., 1991).
2. **Whole-of-landscape** – Earlier manifestations of systematic conservation assessment were developed around the less complex aim of maximizing the representation of biodiversity in reserves. Hence a binary view of the world was initially adopted, where only areas within reserves were considered as contributing to the conservation objective. It is now well recognized that the future of a sizable proportion of biodiversity, if not the majority, is managed and will continue to be managed outside of reserve systems (Cowling et al., 2002; Hutton and Leader-Williams, 2003).
3. **Landscape variegation** – Similarly, in earlier assessment frameworks each part of the landscape was considered either part of a habitat 'patch' or part of the transformed agricultural matrix, where the latter was not recognized as providing any benefits for biodiversity conservation. This patch-based view contrasts with what is now recognized as the heterogeneous and variegated nature of many landscapes, emerging in their forms from a complex mix of past and present management, disturbances such as vegetation clearing and soil erosion, regeneration, and pest and weed invasions. It is generally accepted now that the complex arrays of habitat forms, ranging from agricultural land with scattered paddock trees and derived grasslands to pristine ecosystems, contribute to varying ways and degrees to overall biodiversity persistence (McIntyre and Barrett, 1992; Wiens, 1995; With et al., 1997).
4. **Processes** – Ecological processes, such as foraging, dispersal, predation, and seasonality; fluctuations of vegetation structure and function; as well as threatening processes such as weeds and pests, over-grazing and firewood collection; are by definition dynamic and often involve complex non-additive interactions between multiple factors. These processes are best addressed through mechanistic, or process, models (Ferrier and Drielsma, 2010; Noss, 1990).
5. **Forecasting** – In order to maximize conservation effectiveness, conservation effort should not only address the current status of entities; it needs to consider future prospects. The question needs to be asked 'what benefits would result from removing or reducing the threat of undesirable future impacts?' Similarly, expected 'positive' processes such as regeneration and ecological succession, needs to be recognised.

While assessment methodologies need to be practical, the complexity of ecological systems justifies a degree of complexity in models (see Box 1). This need to balance practicality with realism, comes to the fore with any attempt to integrate combine habitat type, quantity, condition and spatial configuration into SCA. These are properties that are at least partially determined by planning decisions on 'where, what and how' to protect, to re-vegetate, or apply other forms of vegetation management.

It is important that assessment methodologies can recognise the heterogeneity or variegation of landscapes (McIntyre and Barrett, 1992). However, it is not sufficient to focus merely on the physical *pattern* that is readily identified within landscapes. Confidence is also needed that the pattern of habitat is adequate to support landscape *processes* – such as foraging, dispersal and migrations – that underpin species persistence (Loehle, 2004; Turner, 1989).

As mentioned earlier there are a number of SCA tools available, mostly freely, which are suited to different applications. The BFT is quite distinct from C-Plan and Marxan in a number of ways: the data structures employed (gridcells rather than polygonal planning units), the conservation objective pursued (overall biodiversity persistence rather than target achievement), and the outputs produced (the BFT produces benefit surfaces, and interactive evaluation of alternative scenarios, rather than irreplacability maps, reserve selections or optimizations). Another significant difference lays in the tacit mode of operation, in particular BFT's intention to provide incomplete, yet useful, information into decision-making rather than complete planning solutions. The BFT shares a number of features with the Zonation tool. Both are capable of considering high levels of variegation in landscapes through their use of raster data, which allows rapid processing of high resolution datasets comprising millions of planning units. Also as they work with continuous benefit functions, they do not require the setting of conservation targets (Ferrier and Drielsma, 2010; Moilanen, 2012). The BFT further departs from the other tools considered above in that it has been designed from the ground up with a focus on informing whole-of-landscape planning, involving multiple conservation mechanisms – i.e. it is not intrinsically focused on reserve selection. Reserves, while offering the most secure conservation mechanism, in isolation provide little prospect of satisfying all of societies' conservation aspirations (Pressey et al., 2002) and must therefore be considered as part of a broader, integrated conservation strategy involving a range of land uses and tenures.

At this stage the BFT lacks the ease of use of other tools and therefore must be applied collaboratively with the tool's developers. It does not integrate multiple criteria (i.e. it considers biodiversity in isolation) but can readily be applied alongside assessment tools focusing on other values (e.g. New South Wales Department of Environment and Conservation, 2006). Unlike Marxan or Zonation, the BFT is not designed to routinely undertake optimal plan generation, which we have found little demand for in our interactions with an extensive range of real-world planning activities (Ferrier and Drielsma, 2010). However, it has, at times, been incorporated into an optimization framework for the purpose of selecting from a set of costed conservation proposals (e.g. Williams et al., 2012). The BFT does not incorporate site-based assessment which in our experience is best achieved using non-GIS-based tools developed specifically for that purpose (Seddon et al., 2010).

The BFT is designed to serve planning processes that take place within a context of opportunity (Knight and Cowling, 2007) rather than solution generation and is therefore, we believe better suited to 'messy' or 'wicked' problem settings (Rittel and Webber, 1973), involving multiple stakeholders, multiple landuses, multiple conservation mechanisms, uncertain data, and rapidly changing information and conditions.

1.3. Overview of BFT

The BFT model is built on assessment criteria widely recognized as important to conservation planning (see Box 2). It combines fine-grained habitat condition, extent and connectivity into a logical, process-based framework (Fig. 1) employing a raster-data structure.

While maintaining a focus on complementarity, the BFT adopts an architecture that recognizes a region as an integral whole. All locations (henceforth referred to as gridcells or sites), across all land tenures, all land-use histories, and all states or conditions, are recognized as contributing benefits for biodiversity to various

Box 2: Assessment criteria within the BFT

Criterion A – Vegetation communities that have been 'highly cleared', 'degraded' and/or 'fragmented'
Some types of vegetation have experienced higher rates of clearing, degradation and fragmentation in the past than others. Criterion A seeks to recognize that in these types of vegetation:

1. further pressure leads to disproportionately high rates of biodiversity loss;
2. investment in management leads to greater improvements in biodiversity retention; and
3. they are generally located in landscapes also facing ongoing pressures.

In some cases an area contributes to regional biodiversity not only because of the type of vegetation at the site itself, but because of its proximity to other, priority vegetation. In such cases buffering, infilling and linking in and around the priority habitat will yield higher benefits than investing in priority areas alone.
Criterion B – Vegetation communities that are floristically distinct
Vegetation communities that are particularly 'distinctive' in terms of their species composition make a larger contribution to regional biodiversity than communities that share species.
Criterion C – Vegetation condition of sites
The contribution to regional biodiversity of native vegetation in 'moderate to very good condition' is likely to be high, relative to other areas. This is largely because vegetation in moderate to very good condition already has important biodiversity values that can be maintained or enhanced for a modest investment, and management actions to address threats are likely to be more successful than management of areas in low condition.
Criterion D – Neighborhood connectivity of sites
It is widely recognized that native vegetation which is well connected to other native vegetation tends to retain more biodiversity over time and appears more resilient to pressures such as weed invasion than areas of vegetation that are more fragmented (Doerr et al., 2010; Hanski, 1999; Mackay et al., 2010; Merriam, 1984; Nicholson et al., 2006; Soule et al., 2004). Areas of native vegetation which are better connected internally and with adjacent areas are also considered to be more likely to adapt and persist under predicted climate change scenarios (Heller and Zavaleta, 2009).
Source: Drielsma et al. (2013)

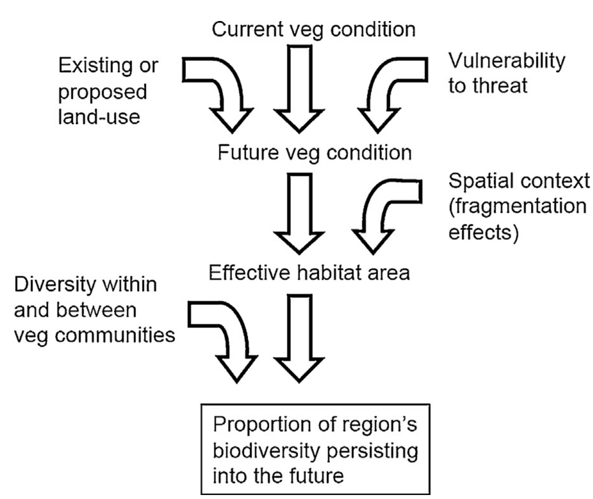


Fig. 1. Diagrammatic illustration of the general framework for modeling biodiversity persistence. A process modeling approach is used that integrates vegetation condition, spatial context and vegetation community representation into a measure of biodiversity persistence.

degrees and in different ways. Thus the model is designed from the ground up to recognize the heterogeneity of landscapes (McIntyre and Barrett, 1992; Wiens, 1995; With et al., 1997; Fahrig et al., 2011) and to view landscapes as a continuum (Fischer and Lindenmayer, 2006). It also recognizes the complementarity in biodiversity composition of individual sites, and the contribution that individual sites make to functional landscape-scale connectivity that enhances biodiversity persistence across the region (Fahrig and Merriam, 1985; Hanski, 1999; Merriam, 1984; Noss, 1990).

The setting of conservation targets is not intrinsic to the approach; rather, targets are considered a special case of the general framework (Ferrier and Drielsma, 2010). The model therefore detects and reports on incremental changes, some of which may not breach target thresholds and therefore might otherwise be overlooked.

The BFT directly addresses three of the assessment modes identified by Ferrier and Drielsma's (2010) forms of SCA:

1. conservation benefits mapping;
2. conservation status monitoring; and
3. interactive evaluation of regional scenarios.

The BFT's regional scenario evaluation quantifies the implications of past or potential future loss, degradation and fragmentation of habitat in a region into practical metrics that quantify 'how much' biodiversity is expected to persist under that scenario. Evaluation metrics can be readily used for reporting, inventorying, monitoring (Noss, 1990) and comparing scenarios. They can also serve as inputs into multi-criteria analyses integrating biodiversity with ecosystem services and socio-economic values such as agricultural production.

Evaluation of scenarios assists planning by:

- enabling the comparison of alternative configurations of management actions across a region (Drielsma and Ferrier, 2006; Ferrier and Drielsma, 2010; Peterson et al., 2003);
- providing the basis for mapping potential management benefits, which form the basis for spatial prioritization (Department of Environment Climate Change and Water NSW, 2010; Ferrier and Drielsma, 2010; Ferrier et al., 2009);
- providing an objective function for optimal plan generation (Williams et al., 2012); and
- assessing the performance of programs by assessing expected changes in biodiversity resulting from implemented actions.

Benefits mapping provides the means to target the features and places in a region where conservation action will provide the greatest improvement in regional biodiversity persistence. In the BFT this is undertaken in two broad steps:

1. the relative conservation status of each vegetation community is established based on the evaluation assessment. This answers the preliminary question of 'what' communities to focus conservation effort on, or more precisely, what are the relative benefits of undertaking conservation action across the set of vegetation communities;
2. this information is integrated with a landscape context analysis in which local habitat condition and habitat connectivity provides the basis for informing 'where' in the landscape conservation efforts will best enhance and improve the viability of biodiversity.

As a minimum, the BFT requires only two raster (gridded) surrogate inputs: vegetation community or ecosystem type mapping and vegetation condition mapping (Parkes et al., 2003; Gibbons and Freudenberger, 2006):

1. Vegetation communities can be represented as either a single categorical map or as a 'stack' of probability surfaces – one for each community – where each provides site-by-site probabilities of the community being present across the region.
2. Vegetation condition is represented as a continuous value surface or a discrete set of classes with relative condition levels.

Across past applications, data inputs have varied according to need and data availability. This has meant differences in: the level of spatial and taxonomic precision; whether or not vegetation condition is treated as classes or continuous surfaces (e.g. Drielsma et al., 2013); and whether and to what level of detail, dynamic processes (regeneration and threatening processes) have been included (Drielsma and Ferrier, 2006). In this sense the most basic BFT model is often supplemented with additional tools and modeling processes (see Appendix B). The basic model is nonetheless useful for providing general information on a region. The degree to which additional input data and enhancements are needed and justified is a judgment left to the practitioners undertaking each project, who are best placed to consider this in relation to the resources available for the project, the purpose for which output will be used, the spatial scale of the assessment (broad-scale assessments can afford to be less spatially precise) and perhaps most importantly, the risks to biological conservation associated with getting the detail wrong.

The reliance on biodiversity surrogates, such as vegetation type and condition, to represent all of biodiversity has been comprehensively critiqued (Rodrigues et al., 2004; Rodrigues and Brooks, 2007; Grantham et al., 2010). However, as planners continue to require practical and timely general decision-support based on best available geographically complete information, surrogates continue to have a role (Ferrier and Guisan, 2006; Margules and Sarkar, 2007; Arponen et al., 2008; Moilanen, 2012). A balance must be found between the risks associated with doing nothing against those arising from acting on imperfect and incomplete information (Burgman, 2005).

Assessments built around vegetation community surrogates are less suited to high-risk recovery planning for individual threatened species where more precise, species-specific information is generally required. For applications such as these, less reliance should be placed on coarse surrogates and, in some cases alternative or supplementary methodologies will be needed.

2. Materials and methods

2.1. Scenario evaluation

The BFT evaluation generates an overall assessment of the study region as well as an assessment of each vegetation community. BFT evaluations, and their extension to the mapping of potential conservation benefits, are built upon the criteria of representation of communities, floristic distinctiveness of communities, vegetation condition, and the connectivity of vegetation (see Box 2). The overall process comprises the following steps (see Fig. 2):

1. Calculate the Effective Habitat Area of each community type;
2. Model the persistence of biodiversity associated with each of these communities; and
3. Integrate persistence across the multiple communities.

In the following sections we describe each step.

2.1.1. Step 1 – Effective Habitat Area

Effective Habitat Area (EHA) is used as the currency for measuring changes to the overall availability of habitat remaining in each

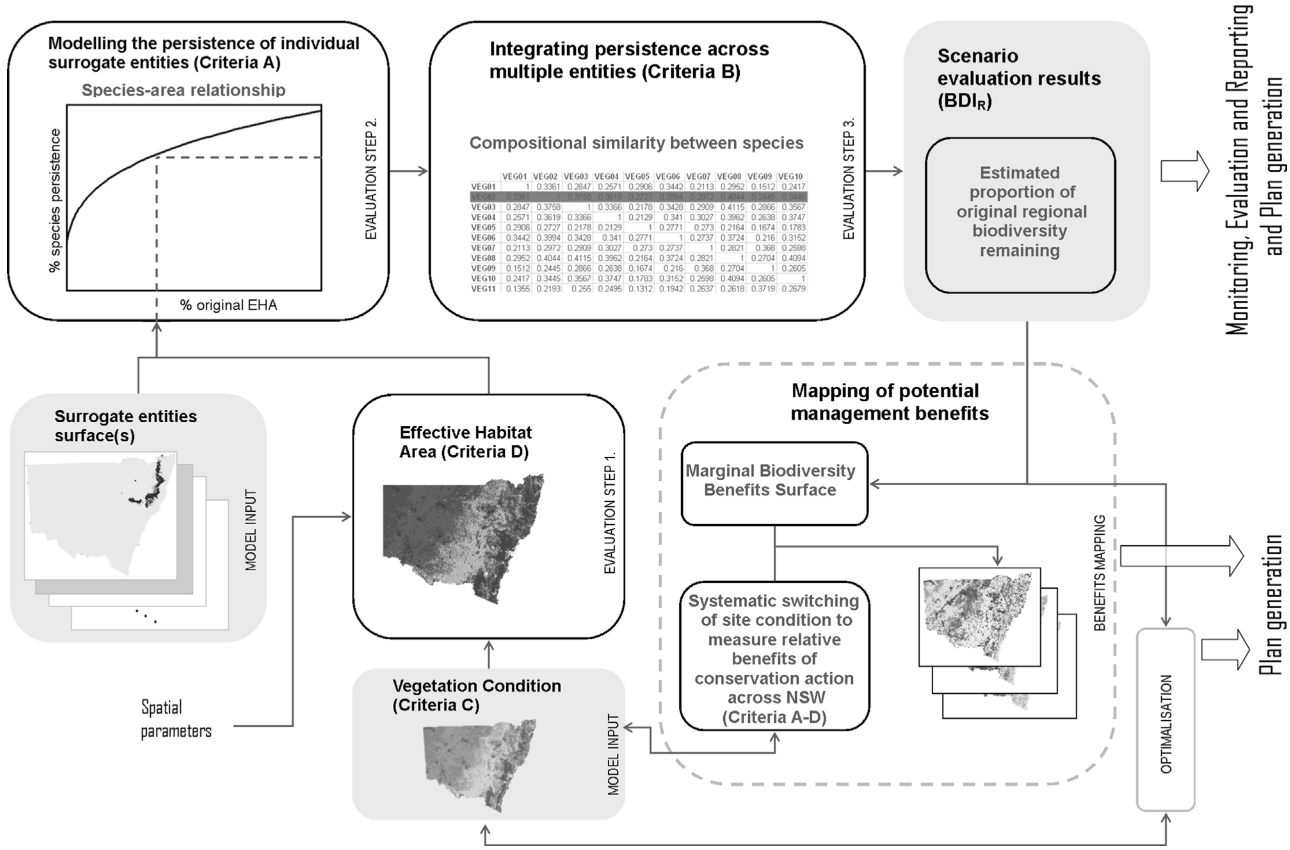


Fig. 2. The overall T-BFT process for regional evaluation and benefit mapping.

Adapted from Drielsma et al. (2013).

community type. It is calculated as the proportion of remaining Colonization Potential (Hanski, 1999), summed across the region. Compared to vegetation extent alone, EHA is a more useful indicator of the proportion of original biodiversity that can be supported by remaining habitat, as it accounts for the extent remaining, its condition (Oliver and Parkes, 2003; Parkes et al., 2003; Thackway and Lesslie, 2005) and its fragmentation (Andrén, 1994; Fahrig, 2002; Sisk et al., 2000).

Colonization Potential for an individual gridcell is calculated as:

$$C_i = \sum_j H_i H_j e^{-\alpha d_{ij}} \tag{1}$$

where H_i is the vegetation condition of the focal cell of interest; H_j is the vegetation condition of a neighborhood location j; d_{ij} is the effective distance from the focal cell i to j; and e is Euler's constant. The mobility parameter (denoted as $1/\alpha$ – a distance, in meters) is used to describe the ability of the biota to move through habitat in a given condition.

As all biodiversity is considered collectively in the BFT, a single range of mobility parameters is assigned that reflects the average movement abilities or critical movement thresholds for target taxa. Since the habitat within any focal cell's neighborhood can be highly variable, a range of $1/\alpha$ values are calculated, the lowest representing areas devoid of native vegetation and the upper value representing 'pristine' native vegetation.

Initially an EHA surface is calculated for the study region using the cost–benefit approach (CBA) method for calculating Colonization Potential over a continuous-value grid, which includes the least-cost paths algorithm and the petals technique (Drielsma et al., 2007). In order to optimize processing speed while minimizing loss of model precision, within each Neighborhood Window, the neighborhood grid-cells are arranged into clusters, or 'petals', which become the reduced set of analysis units for Colonization Potential calculations (see Fig. 3). Petals become larger the further they are from the focal cell, reflecting the reduced need for spatial precision with increasing distance from the focal cell.

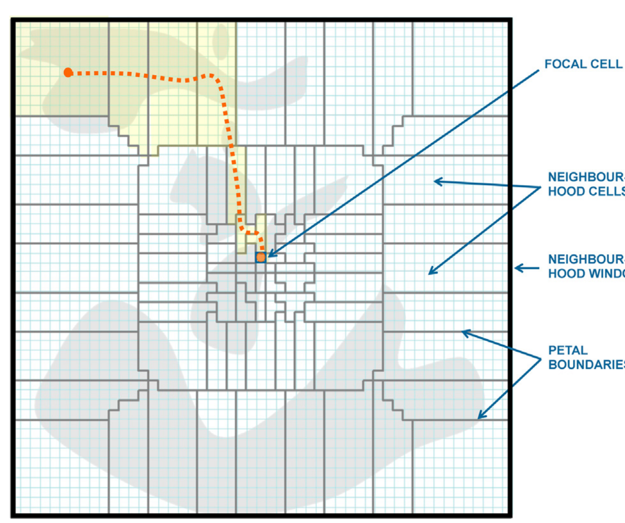


Fig. 3. An example of a petal configuration based on a 51 × 51 source window and a 9 × 9 destination window. Using the LCP algorithm, the yellow petals have been selected to calculate the (hypothetical) 'effective distance' between the focal cell and the top-left petal, simulating the red path that optimizes crossing habitat. The process is repeated for all neighborhood petals and then for all possible focal cells in the region.

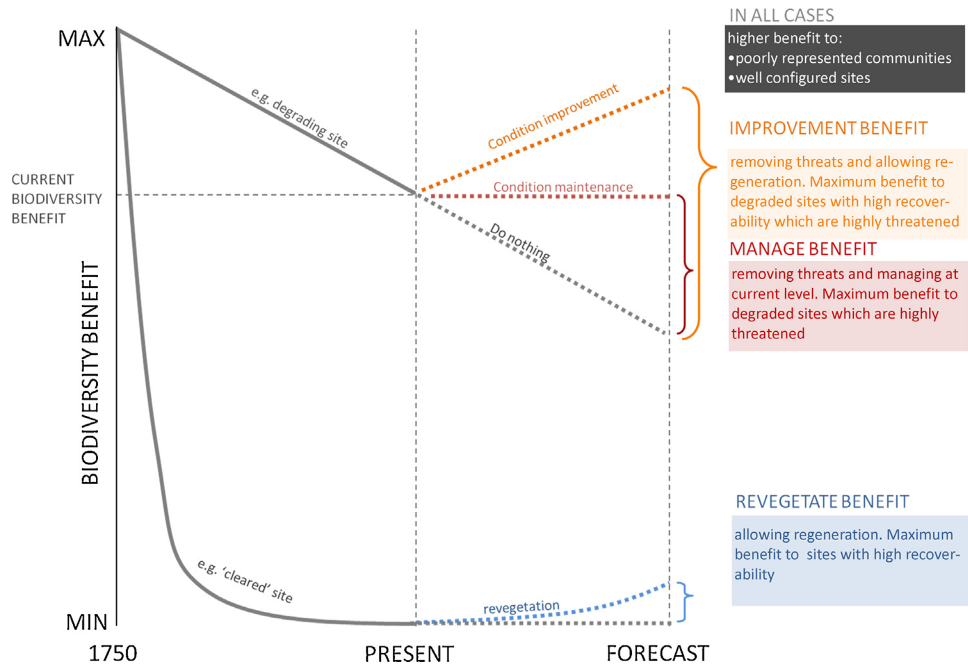


Fig. 4. Graphical representation of hypothetical 'manage' and 'improve' benefits from a degraded site and revegetation benefits from a 'cleared' site. In each case higher benefits accrue to sites supporting or previously supporting under-represented communities and where the site has potential to improve landscape connectivity. In this case these dimensions are kept constant. NB: in the NSW case-study, the do-nothing option was assumed to be total loss (minimum biodiversity benefit).

The CBA component of the model calculates Colonization Potential using a benefit grid and a cost grid. The benefit grid contains the H_i values for each site in the region and the cost grid, the permeability of each site. Permeability is the $e^{-\alpha d}$ component of Eq. (1), where d is the orthogonal or diagonal width of a cell, depending on the angle a least-cost path intersects the cell. Having extracted this information for a neighborhood window, the algorithm calculates the permeability of an entire path by multiplying the permeabilities of each cell along the least-cost pathway. A single deterministic path is calculated between each focal cell and each petal (via other petals) in its neighborhood, and through the whole process the connectivity of every cell to every other cell within a radius of possible relevance (thus the window size) is included. A multitude of possible paths are recognized through the use of petals which makes each path increasingly fuzzy the further away from the focal cell. More fuzziness is introduced as different petal configurations are imposed on the same cells as the analysis window moves. At each instance the same cell can be either a focal cell, part of a 'destination' petal or somewhere along a number of alternative paths.

2.1.2. *Step 2 – Modeling the persistence of biodiversity associated with each community type*

In this stage of the modeling process, EHA is converted into a measure of regional biodiversity outcome. We derive a biodiversity index (BDI_i) for each community type, indicating the proportion of the original species expected to persist within community i. At its simplest BDI_i is a simple transformation of the summed EHA for a community type using the species–area relationship (see Faith et al., 2008 for further detail on the use of the species–area relationship in this context) calculated as $BDI_i = (EHA_i/OHA_i)^z$, where z determines the departure of the species–area relationship from a linear relationship and where OHA is the original extent of the community. A value of $z = 0.27$ is generally used. This value was originally based on a statistical analysis of compositional turnover in floristic survey data, using generalized dissimilarity modeling (Ferrier, 2002; Ferrier et al., 2002) in conjunction with a technique for estimating species–area relationships from turnover data, described by Harte et al. (1999). This value also closely matches values for z used in similar studies around the world (e.g. Nelson et al., 2009).

2.1.3. *Step 3 – Integrating persistence across multiple communities*

The conservation objective from the BFT analysis is generally to maximize the Regional Biodiversity Index (BDI_R) which aggregates BDI_i across all communities. A simple measure of regional biodiversity outcome (BDI_R) can be calculated by summing BDI_i across the communities. However, a further enhancement to the method is achieved by considering the compositional overlap between the communities.

Compositional overlap (Faith and Walker, 1996) is an important consideration in this step as it allows for the distinctiveness of each communities' species composition (where that information is available) to factor into the calculations of conservation benefits (i.e. criteria B in Box 2). Each community has a unique combination of species; but individual species generally occur across a range of communities. By including compositional overlap as a consideration, changes to the summed EHA_i of non-distinct communities (those which share species across a number of other communities) are recognized as having less impact to the conservation objective than communities with species not commonly found outside that community.

Within the BFT the aggregated Regional Biodiversity index for the region (BDI_R), excluding compositional overlap, is simply the sum of the community biodiversity indices. Where compositional overlap is included, it is calculated using the following formula:

$$BDI_R = \frac{\sum_{i=1}^{n}\sum_{k=0.1}^{0\to1.0} o_i\left(\sum e_j/\sum o_j\right)^z/\sum o_j}{\sum_{i=1}^{n}\sum_{k=0.1}^{0\to1.0}\left(o_i/\sum o_j\right)} \quad S_{ij}\geq k \qquad (2)$$

where the original EHA of community i was o_i; and the EHA is e_i. The compositional similarity between communities i and j is s_{ij} where the region is classified into n communities. For each community i, (a nominal) 11 iterations are calculated within the numerator and denominator ($k = 0, 0.1, \ldots, 1.0$). At each step only the

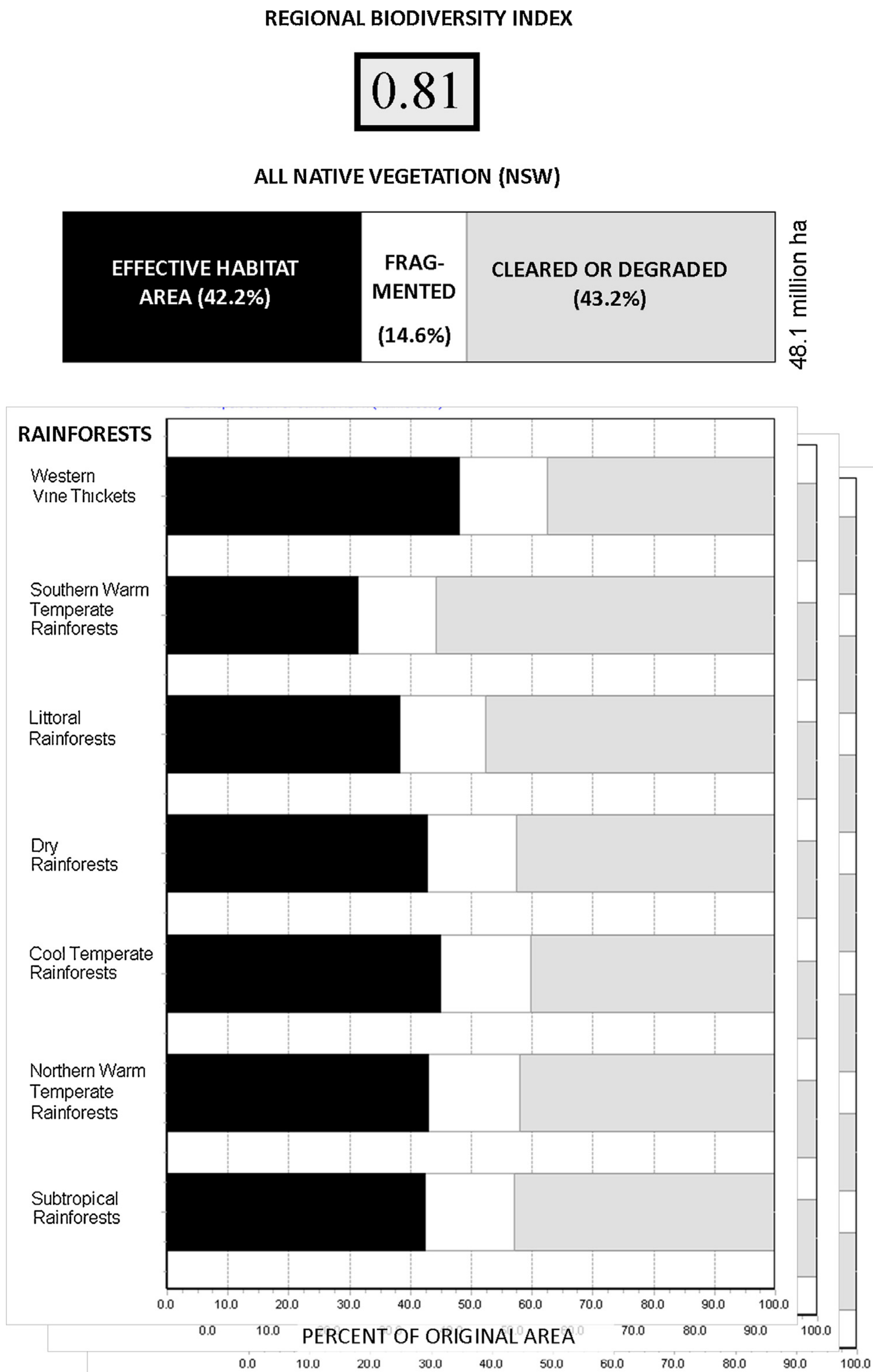
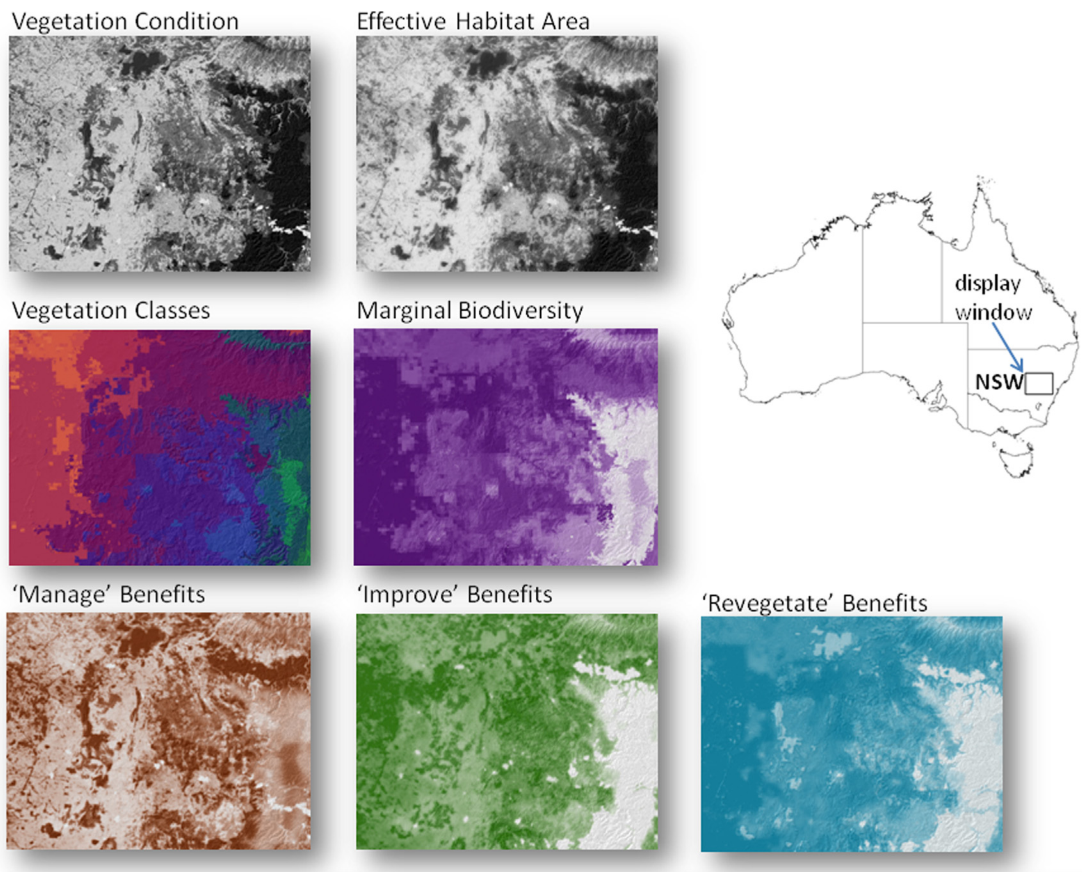


Fig. 5. Example of report card developed from T-BFT outputs for a 25 year future scenario. Included is an example of community-level assessments for rainforest communities (below), the regional assessment (middle) and the Regional Biodiversity Index (above) (resulting from the aggregation of all community assessments). Each chart shows the proportion of original effective habitat lost through clearing and degradation (gray); that lost through fragmentation (white); and the remaining EHA (black).



CONDITION	LOW			MEDIUM			HIGH		
MARGINAL BIODIVERSITY BENEFIT (Mi)	LOW	MED.	HIGH	LOW	MED.	HIGH	LOW	MED.	HIGH
MANAGE BENEFIT	L	LM	M	L	LM	MH	L	M	H
IMPROVE BENEFIT	L	LM	M	L	M	H	L	L	L
REVEGETATE BENEFIT	L	M	H	L	LM	M	L	L	L

Fig. 6. Examples of key spatial inputs and outputs from benefits mapping. The figure shows an example window from NSW, Australia. In each map darker shading indicates higher values except for the 'vegetation classes' map in which areas of similar species composition have been assigned similar color. The table is a summary of how the different combinations of vegetation condition and M_i lead to a range of benefit scores. Colors in the table approximate those in the mapped examples (L – low; M – medium; H – high).

Source: Drielsma et al. (2013).

communities j with similarity to community i greater than or equal to k are included in the calculations i.e. when $k = 0$, all communities are included; when $k = 1$, only community i itself is included.

In the process which led us to settle with Eq. (2), we sought a method that jointly recognizes the integrity of communities as well as the importance of conserving species. Species-level conservation as an objective is self-evident to nearly everyone. We considered recognition of the community-level as also necessary, firstly because unique combinations of species into communities are a recognised level of biological organization (Noss, 1990). Secondly, largely non-distinct communities may include highly distinct components. For example, considering a community made up of 100 species, 99 of which occur widely across other communities and one that occurs nowhere else, the fate of the distinct species may be overlooked if the distinctiveness of the community as a whole, which is low, is an overriding factor in the assessment.

2.2. Conservation benefits mapping

Benefit maps provide a priori guidance of *where* to undertake *what* action in order to maximize improvement to regional biodiversity persistence. The BFT does not consider economic costs of undertaking conservation action or the broader issues of feasibility of undertaking actions across a region. However, benefit maps can be combined with that additional information to produce maps of conservation *priority* for a region – e.g. by dividing the estimated benefit of implementing a given action in each cell by the estimated cost of that action, thereby estimating conservation priority in terms of cost-effectiveness or return-on-investment.

The BFT benefits mapping methodology does not work with a spatially explicit scenario and therefore cannot fully anticipate representational and spatial configuration complementarities arising from a particular set of conservation actions. Rather, it performs a generic analysis by systematically applying a hypothetical conservation action to each individual cell in turn, or to a cluster of cells in turn (i.e. localized scenarios) subject to petal configuration (see Fig. 3). In some cases, for example where spatially related changes need to be assessed (e.g. for designing a wildlife corridor), a scenario planning approach may be a more appropriate approach.

In order to produce benefits mapping, the BFT first must perform an evaluation of the study region. This can be applied to the region in its current state, in which case the benefits identified are in relation to this state; or, by drawing on future condition modeling (Drielsma and Ferrier, 2006) such that the forecasted future state of the region becomes the basis for a more strategic, forward-looking approach to benefits mapping.

In the BFT, the overall conservation status of vegetation communities is assessed and combined based on Criteria A–D (Box 2). The status of individual communities, derived from the regional evaluation, is relayed to a benefits mapping analysis where local vegetation condition and neighborhood connectivity (Criterion C and D) are included in determining potential benefits, individually for each location. The regional evaluation is essentially a vegetation community-level assessment based on landscape conditions within the region; whereas benefits mapping is a landscape-level assessment based on the condition of communities found within the landscape. The former calculates indices for a single regional scenario; the latter produces maps where each gridcell represents a scenario evaluation of applying conservation action at that general (subject to petal configuration) location.

The benefits mapping methodology assumes that higher benefit will accrue by undertaking management in settings where:

- a positive response (improved vegetation condition) is expected at the site;
- functional connectivity exists to other habitat;
- the location supports a floristically distinctive vegetation type; and/or
- the resident vegetation community has generally been highly cleared, degraded and/or fragmented across the region.

Conservation Benefits are calculated by systematically estimating the marginal impact on BDI_R of applying a 'hypothetical' localized conservation action (referred to as petal switches) across the region. A separate benefits map is therefore generated for each action of interest. The actions considered typically include: management aimed at maintaining habitat in its current state (removing threats); management aimed at improving habitat condition (and therefore the capacity to support higher levels of biodiversity); and revegetation of areas previously cleared of native vegetation (see Box 3 and Fig. 4).

Reflective of how complexity builds exponentially as factors are introduced, the benefit scores of any given gridcell emerges as a result of interactions between the conservation status of the relevant community (M_i, see below), the vegetation condition of the cell, and its position in terms of its connectivity to other parts of the landscape. As the methodology is based on neighborhood window calculations, the impact of switches on BDI_R are also influenced by the M_i and EHA values of neighborhood cells i.e. when a cell with high M_i or EHA value is processed as a focal cell, the benefit scores of cells within its neighborhood are boosted.

Rather than fully re-calculating BDI_R across the entire study region at the point of each switch, a rapid approximation of changes to BDI_R is employed. The switching technique and BDI_R re-calculations are undertaken within landscape-scale neighborhood windows using pre-calculated Marginal Biodiversity Benefit values (from the initial evaluation stage) for each vegetation community (M_i). M_i captures relevant information on regional complementary for community i. For each community, M_i equates to the increase in BDI_R from the current level when e_i is replaced with o_i in Eq. (2).

For each window, the BFT initially estimates the window's contribution to BDI_R for the current state, based on the current condition of vegetation; then estimated changes to BDI_R arising from

Box 3: Conservation benefit mapping for NSW

Manage benefits apply to extant native vegetation and are derived by systematically switching the condition of (petal) locations to simulate clearing of native vegetation. At each step the altered petal's habitat and permeability were set to the minimum values (H = 0; $1/\alpha$ = 2000 m) and the change to BDI_R re-calculated. The switching process has the effect of reducing the BDI_R through direct loss of habitat at the focal cell when it is altered in the moving window analysis, and by reducing the habitat of neighborhood sites, when they are part of an altered petal.

The magnitude of the loss in regional BDI_R caused by clearing equates to the relative benefit of preventing that loss. Clearing an area that reduces connectivity and condition of a poorly protected vegetation community will result in a relatively large decrease in regional BDI_R (although the absolute value will be very low), and translate into a high benefits for management of that location.

Areas with high 'Manage' benefit' are intended to highlight the best remaining examples of vegetation communities that address all criterion. The analysis assigns a higher benefit to sites that are in better condition. However, once other attributes are taken into account in the analysis, high manage benefit areas can range in condition from 'moderate' to 'very good'.

Improve benefits apply mostly to partly degraded extant native vegetation – where the alternative land-use involves allowing the current vegetation condition to improve passively by removing the pressures, such as grazing, that otherwise prevent such improvement.

The areas identified as having high 'Improve' benefit are typically areas with vegetation that are in moderate condition and score highly across the other criteria. With appropriate management, areas such as these can provide improved biodiversity outcomes within a relatively short timeframe and with minimal effort.

Revegetate benefits apply to degraded and cleared native vegetation and is derived by systematically changing the condition of each location to simulate it being repaired to its pre-cleared state (H = 1000; $1/\alpha$ = 5000 m). The increase in regional BDI_R caused by repairing the grid cell becomes the relative benefit for repair. Repairing an area (grid cell) that improves connectivity and improves condition of a poorly protected vegetation community will result in a relatively large increase in regional BDI_R and translate into a high priority for revegetation.

Areas with high 'Re-vegetate' benefit are predominantly cleared or highly degraded (i.e. low in criteria C) examples of either existing or 'original' vegetation types that score highly across the other criteria.

Source: Drielsma et al. (2013)

Box 4: Steps for calculating conservation benefits

1. The current benefit score of a focal cell is calculated as:

$$B_f = M_i C_i \quad (3)$$

2. Each set of cells, or petals (see Fig. 3), surrounding the focal grid-cell is switched, in turn, to alternative values reflecting changed management corresponding to the three benefit types;
3. Following each switch, the change in benefit is calculated for the window. That value is divided equally among all the cells making up the altered petal and the apportioned values are incremented to the same corresponding cells in the output grid;
4. This process is repeated for all 'petals' within a neighborhood window;
5. Steps 1–4 are repeated for every grid-cell.

hypothetical management changes for each petal are systematically recalculated (see Box 4).

3. Results

We draw on the recent NSW Native Vegetation Management Benefits Analysis (Drielsma et al., 2013) as a case study to illustrate the utility of the BFT.

Development of the NVM benefits map outputs were originally commissioned by the Office of Environment and Heritage (Department of Premier and Cabinet, New South Wales) to address the need to target investment in biological conservation to areas that maximize positive impact on biodiversity at that scale. Development of the outputs was preceded by publication of a map of state-scale investment 'priorities' in the Draft NSW Biodiversity Strategy (Department of Environment Climate Change and Water NSW, 2010). Formal comments on the map provided as part of a public exhibition of the Strategy concluded that the mapped areas lacked sufficient rigor and flexibility to reflect the context in which they would be used. This resulted in development of the methodology described here to derive biodiversity benefits outputs that would meet the needs of:

- Catchment Management Authorities involved in review and upgrade of statutory catchment action plans;
- other public land management agencies, including local government, to target investment in native vegetation management; and
- non-government organizations and landholders, to assist their development of applications for grant funding under available government programs.

3.1. Evaluation

An evaluation of the current scenario for NSW based on the Keith (2004) class-level vegetation mapping was undertaken. Fig. 5 shows the results from the evaluation for each class within the rainforest vegetation formation (as an example) as well as the aggregated evaluation across all vegetation types.

3.2. Conservation benefits mapping

Fig. 6, an example from the NSW statewide assessment (Drielsma et al., 2013), provides a comparison between spatial data inputs (condition and vegetation communities); intermediate data (EHA and Marginal Biodiversity), and benefits outputs. The lower chart provides a lookup to compare combinations of condition states, vegetation community states (M_i), and the output benefit surfaces. In this assessment three potential benefit maps were produced: 'manage benefits', essentially the best remaining examples of under-represented communities; 'improve benefits', degraded examples of under-represented communities; and 'revegetate benefits', areas formerly supporting under-represented communities where native vegetation has been removed. These outputs are available for download at http://www.environment.nsw.gov.au/research/AncillaryVegetationProductsDataInventory.htm or by contacting the authors. In each case a benefit premium is applied to areas where landscape connectivity (especially of under-represented remnant vegetation) can be enhanced.

4. Discussion and conclusions

The BFT was developed in response to the need to extend systematic conservation assessment to better synthesize the effects of pattern- and process-based factors on biodiversity (Turner, 1989; Ferrier and Drielsma, 2010) and to help answer the basic questions of 'how much biodiversity will persist, what to protect and where to do it' through a community-level assessment. The toolkit provides a single underlying methodology for forward planning, evaluation and monitoring. It incorporates design features that integrate an ability to consider complex scenarios involving a range of landuses, each affecting overall biodiversity in different ways. It considers variegation and fragmentation in a process model. Unlike other more widely used tools, it is designed to provide guidance rather than planning solutions. However, it generates outputs that can readily be combined with species-level assessment, non-biodiversity attributes, and estimates of the cost and feasibility of actions in a subsequent process.

The issue of spatial scale has been touched upon in this paper. It remains a live issue in conservation planning and in the use of the BFT. The case-study we presented here represents a broad-scaled analysis which provides big-picture insights into the state of biodiversity and where generally in the state of NSW to undertake actions to best improve the prospects of the state's biodiversity, based on a set of criteria understood to drive biodiversity persistence. In regional-scale natural resource management planning across NSW these big-picture benefit surfaces are currently being supplemented with fine-scale regional assessments (including fine-scale BFT assessments) that add consideration of local conditions, the needs of specific taxa and other values such as ecosystem services (e.g. Murray Catchment Management Authority and Office of Environment and Heritage, New South Wales, 2012). Advice has been provided to NSW Catchment Management Authorities on how to incorporate the layers into their Catchment Action Plans (NSW Office of Environment and Heritage, 2012).

We consider this strategy of linking scales, of integrating big-picture conservation with detailed local considerations as a powerful way of engaging with the human communities upon whom successful conservation depends.

The BFT software has undergone a lengthy period of iterative development coupled with application to real-world assessments beginning around 2002 (New South Wales Department of Environment and Conservation, 2004). The application was initially developed as an extension to ESRI's Arcview GIS with calls to DLLs coded in C++. The Arcview version was used extensively for the following decade. In 2011 it was re-written to produce a user-friendly, stand-alone .NET application with built-in charting capacity. At present the software can be obtained by contacting the authors (GM, MD). In past applications third party users of the software have engaged with the BFT development team to various degrees throughout their assessment process. We are iteratively improving usability, access to software and user-documentation.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2013.11.028.

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